

Evaluation of reanalysis surface wind products with quality-assured buoy wind measurements along the north coast of the South China Sea

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Abstract

Three archived reanalysis wind vectors at 10 m height in the wind speed range of 2–15 m/s, namely, the second version of the National Centres for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSv2), European Centre for Medium-Range Weather Forecasting Interim Reanalysis (ERA-I) and NCEP-Department of Energy (DOE) Reanalysis 2 (NCEP-2) products, are evaluated by a comparison with the winds measured by moored buoys in coastal regions of the South China Sea (SCS). The buoy data are first quality controlled by extensive techniques that help eliminate degraded measurements. The evaluation results reveal that the CFSv2 wind vectors are most consistent with the buoy winds (with average biases of 0.01 m/s and 1.76°). The ERA-I winds significantly underestimate the buoy wind speed (with an average bias of -1.57 m/s), while the statistical errors in the NCEP-2 wind direction have the largest magnitude. The diagnosis of the reanalysis wind errors shows the residuals of all three reanalysis wind speeds (reanalysis-buoy) decrease with increasing buoy wind speed, suggesting a narrower wind speed range than that of the observations. Moreover, wind direction errors are examined to depend on the magnitude of the wind speed and the wind speed biases. In general, the evaluation of three reanalysis wind products demonstrates that CFSv2 wind vectors are the closest to the winds along the north coast of the SCS and are sufficiently accurate to be used in numerical models.

Key words: evaluation, quality control, buoy wind, coastal regions of the South China Sea

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1 Introduction

Surface wind is one of the major factors in the generation and movement of ocean currents and waves, constituting a forcing role in ocean and coupled models. Accurate global high-resolution surface winds are critical for improving numerical weather prediction and climate model forecasting (Large et al., 1991; Josse et al., 1999; Bourassa et al., 2010). Surface ocean winds are commonly measured by *in situ* techniques or remote sensing instruments. Buoys are moored with the primary goal of sustained marine observations. China has arranged an intensive offshore buoy observation network, especially in the East China Sea and South China Sea (SCS). This network offers real-time meteorological and marine monitoring, which is quite valuable for fishery industries and other marine activities. However, due to the uniformity of moored buoys, buoy winds are not the appropriate input parameters in climate models. Instead, the most available forcing of ocean movement in models is remote sensing winds or reanalysis wind products. But these wind products have limited spatial resolutions which are not sufficient to resolve small-scale processes, especially in coastal regions. Spatial resolution problems would bring increase in errors to the gridded wind products.

Scatterometer wind data are found to degrade near shore (Tang et al., 2004) due to the inadequacy of the geophysical model function in addressing coastal conditions and light winds situations. Moreover, reanalysis wind products are the result of assimilation by multiple observations, the accuracy of which is heavily dependent on the accuracy of original data and the skills of assimilation. It is suggested that reanalysis wind products have limited ability in depicting surface winds in coastal waters (Schmidt et al., 2017). Therefore, it is necessary to perform the evaluation of reanalysis wind products to investigate how these datasets represent real wind fields at the air-sea interface in coastal regions.

In evaluation studies, *in situ* winds observed by buoys are considered true winds (Ebuchi et al., 2002; Tang et al., 2004; Yang and Zhang, 2018). However, without normal functioning or effective calibration of buoy sensors, automatic measurements by buoys would be invalid which cause large biases. Moreover, those erroneous but seeming like reasonable observations may lead to an incorrect analysis of the weather or climate change. These remaining problems result in unreliable and meaningless evaluations. As a result, it is important to detect and reduce the degraded measurements of moored buoys prior to evaluating the

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accuracy of other data archives.

In fact, before collecting buoy records, gross errors in real-time data have already been removed by automatic algorithms. These errors are typically caused by transmission problems or power system degradation. However, as Gilhousen (1998) mentioned, these checks have done a poor job of detecting errors due to sensor degradation. The National Data Buoy Center (NDBC) has made great efforts to address this problem. An extensive, after-the-fact validation programme was introduced to perform the data quality control of NDBC stations (Gilhousen, 1998). For example, if the ratio of gust-to-mean wind speed is greater than 4 or less than 1, no wind speed would be transmitted. In addition, one procedure could detect significant sensor failures automatically and switch to a backup sensor if it could exhibit better time continuity and transmit reasonable values. These changes could effectively increase the overall amount of data while decreasing the chance of degraded measurements being transmitted.

The National Oceanic and Atmospheric Administration (NOAA) designed the tropical TAO/TRITON array to better understand and predict climate variations related to the El Niño–Southern Oscillation (ENSO). TAO/TRITON was built over decades and is presently acknowledged to provide high-quality buoy data for climate analyses. The automatic quality control procedures for real-time data are listed in three major items: preliminary gross automated error checks, daily parameters that generate error alerts and additional daily checks. However, they admitted that some questionable data that cannot be automatically removed are checked by experienced data analysts.

The quality control analysis performed on NDBC buoys and TAO/TRITON suggests a good reference for the quality assurance of buoy measurements in China waters. The aim of this study is to determine which reanalysis wind product best represents the wind field in the study location, while the real wind field is characterized by buoy winds after quality control. In the present study, wind vectors observed by buoys are first checked and modified by eliminating the degraded measurements, as there are no backup sensors. The buoy winds after quality control are compared with Cross-Calibrated Multi-Platform (CCMP) surface wind vectors in order to ensure that there is no significant deviation. The accuracies of different reanalysis wind products are given in this study by comparison with quality-assured buoy winds. Three reanalysis wind products are evaluated here: the second version of National Centres for Environmental Prediction (NCEP) Climate Forecast System reanalysis data; European Centre for Medium-Range Weather Forecasting (ECMWF) Interim reanalysis data; NCEP-Department of Energy (DOE) reanalysis 2 data. This paper is organized as follows: The data and evaluation methods used in this study are described in Section 2. The quality control procedures are described in Section 3. The results of the evaluation are presented and discussed in Sections 4 and 5, respectively. The findings are concluded in Section 6.

2 Surface wind datasets and evaluation techniques

2.1 Data

2.1.1 Buoy data

The buoy data used in this study were obtained from the South China Sea branch of the Ministry of Natural Resources of PRC. The wind monitors fixed on buoys are model 05103 produced by the R. M. Young Company. The wind speed and direction sensors measure horizontal winds at a height of 10 m above

the sea surface and have measuring ranges of 0–100 m/s and 0°–360°, respectively. The estimated accuracies of the buoy wind speed and direction are 0.3 m/s and 3°, respectively. Different from reanalysis winds, buoy wind vectors are measured hourly by averaging instantaneous winds 10 minutes before the hour. According to the 6-hourly temporal interval of reanalysis wind products, we modified the buoy winds to make the evaluation available by extracting buoy data at the corresponding time points.

2.1.2 NCEP Climate Forecast System reanalysis (CFSv2) data

CFSv2 was implemented into operations in March 2011. This version has upgraded nearly all aspects of the data assimilation and forecast model components of the system (Saha et al., 2014). CFSv2 provides ocean surface wind vectors at 10 m reference height, which corresponds to that of buoy winds. The temporal interval of CFSv2 winds used in this paper is 6 hours and the grid spacing is 0.31°×0.31° (approximately 33 km).

2.1.3 ECMWF Interim reanalysis (ERA-I) data

ERA-I is a global atmospheric reanalysis dataset available on 60 vertical levels from the surface up to 0.1 hPa (Dee et al., 2011). The data assimilation system used to produce ERA-I includes a 4-dimensional variational analysis introduced by the ECMWF. It covers the period from 1979 to the present with a 6-hourly temporal interval. The spatial resolution of the dataset we obtained is 0.75°×0.75° (approximately 80 km).

2.1.4 NCEP-DOE reanalysis 2 (NCEP-2) data

NCEP-2 is an improved version of the NCEP Reanalysis I model with corrected errors and updated parameterizations of physical processes (Kanamitsu et al., 2002). It provides 10-m *U*-wind and *V*-wind data 4 times per day from 1979 to the present. This wind product has global coverage with a T62 Gaussian grid (192×94), indicating that the horizontal resolution is approximately 200 km.

2.1.5 Cross-Calibrated Multi-Platform (CCMP) data

The V2 CCMP processing now combines Version-7 RSS radiometer wind speeds, QuikSCAT and ASCAT scatterometer wind vectors, moored buoy wind data, and ERA-Interim model wind fields using a Variational Analysis Method to produce gridded vector winds. Daily surface wind dataset covers the global ocean with 6-hour and 0.25° (approximately 25 km) resolution.

2.2 Evaluation approaches

2.2.1 Data collocation

After a quality control analysis on the moored buoy wind measurements, reanalysis winds were collocated with modified buoy winds. This collocation procedure needs to match the datasets temporally and spatially. The reanalysis winds are all obtained with 6-hourly temporal resolution. Therefore, the corresponding 4 collection times (00:00, 06:00, 12:00, and 18:00 UTC) of the buoy winds are extracted to produce wind pairs. In terms of the spatial grid, however, the values of the variables in every grid in the reanalysis datasets represent the mean value in the grid box centred on the corresponding geographic coordinates. In this study, based on triangulation-based linear interpolation, all reanalysis and scatterometer wind products are interpolated onto the corresponding location of buoys before evaluation. The locations of the buoys in quality control are marked in Fig. 1.

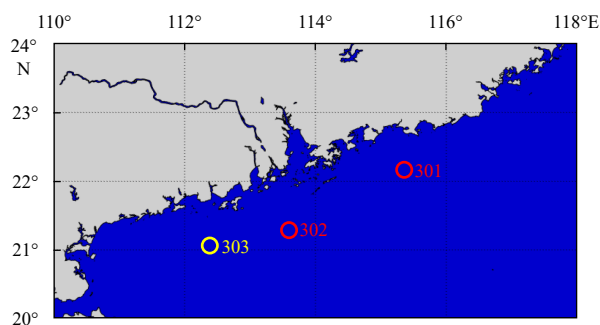


Fig. 1. Location of the three offshore-moored buoys (hollow circles) used in the quality control. Red circles denote the selected buoys in the evaluation.

2.2.2 Statistical methods

A variety of statistical analyses were used to compare the wind collocations. The scatter distribution of the reanalysis wind products was first illustrated to compare their consistency with the observed winds. This approach also offers a rough check of the error dependence on the wind speed.

Statistic parameters such as the root-mean-square error (RMSE) and correlation coefficient (R) were calculated to assess the ability of different wind products to represent the variability in the observed winds. The bias (mean of residuals) was also calculated to evaluate the tendency of the reanalysis winds, which may overestimate or underestimate the buoy measurements. In addition, probability density functions (PDFs) were used to evaluate the description of wind regimes by different reanalysis wind products.

3 Quality assurance techniques

3.1 Buoy quality control

Surface winds (2012–2014) from 5 moored buoys were first obtained. However, due to anthropic or natural factors, buoys may drift unpredictably, and their locations need to be checked first. Data from moored buoys that have drifted more than 1 degree of latitude or longitude are excluded from the dataset during quality control and the subsequent evaluation. Considering the continuity and amount of buoy data (Table 1), the surface winds of Buoys 301, 302, and 303 from 2012 to 2013 are obtained for further quality control.

3.2 Data quality control

The buoy data undergo extensive quality control analysis to

ensure that they meet stringent accuracy standards. Table 2 summarizes the preliminary procedures for real-time buoy data.

The missing values of hourly wind speed or direction are first complemented with default values for time continuity. The range check ensures that all measurements fall within reasonable upper and lower limits. The lower limit of wind velocity is set at 2 m/s to exclude unreliable wind directions at a low wind speed. The original time series of three buoy wind observations are shown in Figs 2 and 3, indicating that most buoy wind speeds are less than 25 m/s. The second check is the extreme-anomaly check with a threshold of maximum allowable difference (M). M is defined by 3 times the standard deviation (STD) of the wind speed. If the value difference with the last observation is greater than M , this observation is regarded as an erroneous value that should be replaced with default value. It is acknowledged that rapid changes could occur in the wind speed due to tropical cyclones. However, the value of M assigned here is large enough that the hourly changes during tropical cyclones are well expressed after quality control. Finally, owing to the functional errors of sensors, erroneous values last for limited periods and require consecutive anomaly checks. The original observation is smoothed to obtain 7-hour running mean wind speed data. It is checked whether the difference between two time series is limited within ± 0.8 STD. If the difference is outside of this range, the corresponding observation is recorded as the default value.

Quality control of wind direction is first dominated by checking the wind speed. It turns out that many erroneous values of wind direction are related to missing (e.g., wind measurements from Buoy 303 from February to May in Fig. 2 or erroneous (e.g., wind measurements from Buoy 301 from February to April in Fig. 3) wind speed observations that should be filtered. However, extreme values remain in the wind direction after the check above, which are close to 360°. These records would amplify the errors in the evaluation by affecting the data stabilization. As a result, these extreme values are removed by setting a higher value of M considering the frequent and significant changes of wind direction. Similarly, consecutive anomalies are also examined with higher threshold.

It is acknowledged that surface wind vectors in the SCS are characterized by significant seasonal cycles controlled by monsoon activity. As shown in Figs 2 and 3, quality-assured wind speeds are relatively high in boreal wintertime and the corresponding wind directions are fixed as prevailing northerlies. In contrast, wind speeds in summer are rather small except during the specific weather processes. These low wind speeds are accompanied by frequent shifts in the wind direction. All the characteristics mentioned above are in accordance with seasonal pat-

Table 1. Variation of buoy location from 2012 to 2014

Buoy ID	2012	2013	2014
301	22.17°N, 115.36°E	22.17°N, 115.36°E	–
302	21.30°N, 113.60°E	21.30°N, 113.60°E	–
303	21.07°N, 112.38°E	21.07°N, 112.38°E	22.17°N, 115.36°E

Note: – means no observation was conducted by this buoy.

Table 2. Major data quality control procedures

Measurement	Range error checking	Extreme-anomaly checking	Consecutive anomalies checking
Wind velocity	speed values outside 2–25 m/s	speed changes more than 3.0 STD from the previous hour	difference between the original and 7-hour-running mean wind speed outside -0.8 STD to 0.8 STD
Wind direction	following the check of the wind speed; the wind direction outside 0° – 360°	following the check of the wind speed; direction changes more than 10 STD from the previous hour	following the check of the wind speed; difference between the original and 7-hour-running mean wind direction outside -5.0 STD to 5.0 STD

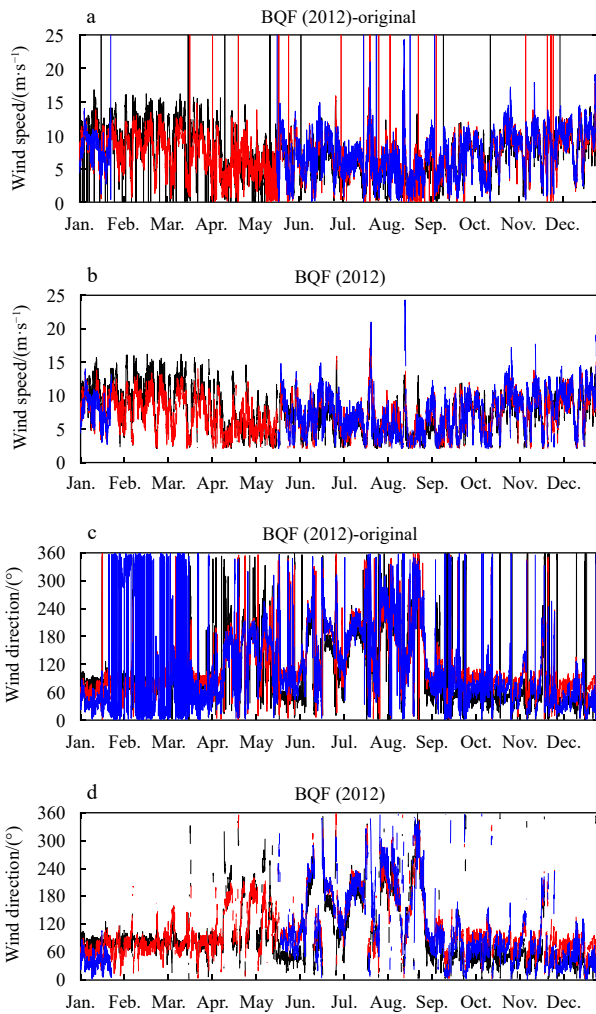


Fig. 2. Time series of the original buoy wind speed during 2012 (a), the buoy wind speed during 2012 after quality control procedures (b), the original buoy wind direction during 2012 (c), and buoy wind direction during 2012 after quality control procedures (d). The black, red and blue lines correspond to Buoy 301, Buoy 302 and Buoy 303, respectively. BQF means the buoys in shallow waters.

terns but are partly covered by abnormal values in the original wind data. Besides, it is obvious that many error signals have been deleted in the time series of wind direction. However, due to the limited threshold values, it seems impossible to delete all the noise of wind direction especially during boreal wintertime. But in boreal summer and autumn, the disordered wind directions may be reasonable because the real winds vary rapidly associated with the lower wind speed. After preliminary validation techniques, the quality of winds observed by buoys is highly elevated, although many degraded measurements are deleted (Figs 2 and 3).

3.3 Buoy data contrast

Due to the close location of these three buoys, data comparison between different buoy measurements can be implemented as an additional check. This procedure is conducive to selecting the best quality buoy data. First, the amount of buoy data was compared. Long data gaps in the time series of wind measure-

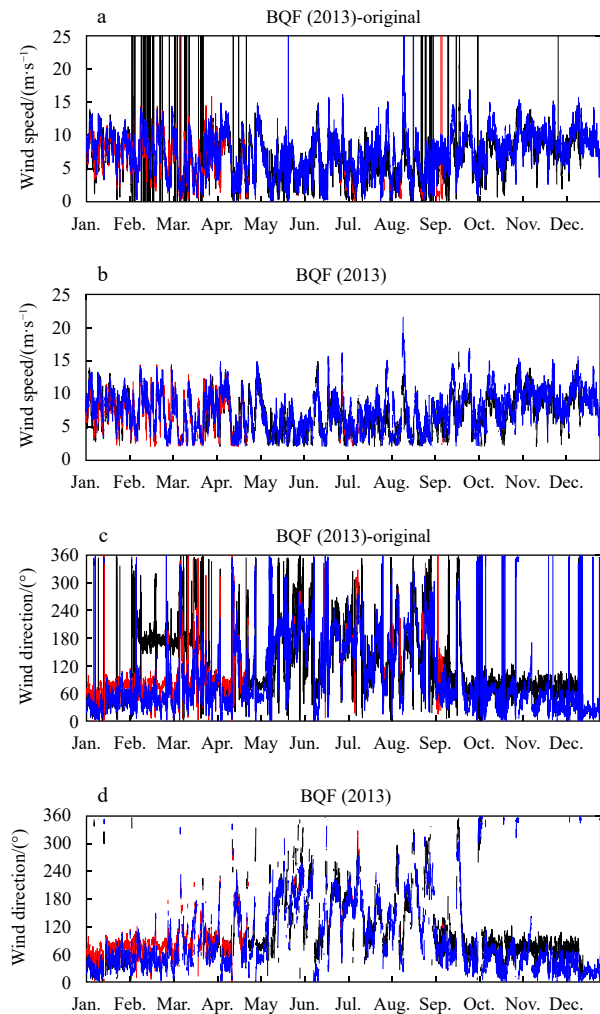


Fig. 3. Time series of the original buoy wind speed during 2013 (a), the buoy wind speed during 2013 after quality control procedures (b), the original buoy wind direction during 2013 (c), and buoy wind direction during 2013 after quality control procedures (d). The black, red and blue lines correspond to Buoy 301, Buoy 302 and Buoy 303, respectively.

ments from Buoy 303 in 2012 and Buoy 302 in 2013 may lead to a small sample size for evaluation, suggesting a higher probability of failure in sensor functioning. Furthermore, two typhoons took place close to the three buoys during the observation time period: Typhoon Vicente (July 22 to 25, 2012) and Typhoon Usagi (September 17 to 23, 2013). It is clear that the rapid variation in the wind speed and direction during the typhoons are well expressed by the buoy measurements except Buoy 302 winds in 2013 since there was no record. However, there are also some other rapid variations, which may be erroneous measurements as there were no occurring of special weather processes. For example, compared to the wind measurements from the other two buoys, the data from Buoy 303 show anomalously high wind speeds during August in both 2012 and 2013, when there was no typhoon or other specific weather processes. These potentially erroneous winds are replaced with the default value as in the quality control.

The SCS is controlled by monsoon circulation, which exhibits prevailing northerlies in boreal winter. The data from Buoy 302 in

2012 and Buoy 301 in 2013 show the most stable winds among all the buoy measurements. According to all these quality control procedures, the best quality buoy winds are from Buoy 302 in 2012 and Buoy 301 in 2013.

3.4 Comparison with remote sensing winds

The scatter diagrams of comparisons of wind speed and direction between selected buoy winds and CCMP surface winds are shown in Fig. 4. In general, buoy winds are quite consistent with CCMP surface wind vectors. Apparently, there are no significant systematic deviations in either wind speed or wind direction. The wind directions of two datasets are agreed for almost all different directions. A further comparison was conducted using statistical parameters of errors, such as the mean bias, RMSE, and the correlation coefficient (Table 3). The average biases of wind speed (0.20 m/s) and wind direction (3.95°) show small deviations which are close to the estimated accuracies of buoy winds. In addition, the average RMSEs are 1.59 m/s and 32.70° for wind speed and wind direction, respectively. The correlation coefficients of both wind speed and wind direction are larger than 0.8 in each year. It is confirmed that the statistical errors above are of the similar magnitude to that of surface winds along the west coast of North America (Tang et al., 2004). The overall results indicate that buoy winds after quality control could be used in the evaluation of reanalysis wind products as true surface winds.

4 Evaluation results

4.1 Comparison of the wind speeds and directions

The reanalysis surface wind vectors during 2012 and 2013 are compared with the quality-assured buoy wind data. Data pairs totalling over 1 200 (over 900) from the selected buoys in 2012 (2013) are collocated by the method introduced in Section 2. The scatter diagrams of the comparisons of the wind speeds and directions are illustrated in Figs 5 and 6. Generally, the buoy wind speeds were largely underestimated by the ERA-I winds. Moreover, the dispersive scatterplots of the NCEP-2 wind speeds and directions indicate less consistence with the buoy winds than the other two reanalysis products.

The statistical parameters of errors between buoy and reanalysis wind products are given in Tables 4 and 5. The biases (RMSEs) of different reanalysis wind speeds compared with buoy data are between -1.57 m/s and -0.01 m/s (1.61 m/s and 2.45 m/s), of which NCEP-2 wind speeds present the largest RMSEs in both years. Due to the consistent scatters of CFSv2 wind speeds, statistical errors between CFSv2 and buoy data reveal the smallest RMSEs. However, the mean biases of wind speeds between ERA-I and buoy data reveal notable negative values, implying a systematic shift in ERA-I wind products. Chelton and Freilich (2005) found that 10-m wind speeds from ECMWF are systematically lower than satellite observations. Such bias could lead to wind stress bias of more than 10%, which potentially induces erro-

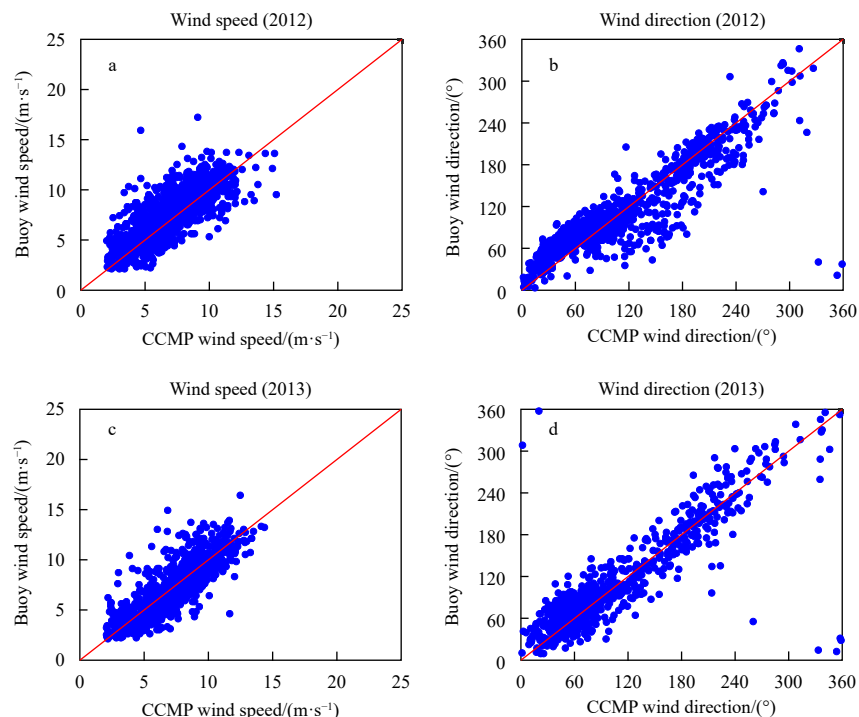


Fig. 4. Scatterplots for the wind speed and direction of the comparisons between the CCMP and wind data from Buoy 302 during 2012 and Buoy 301 during 2013. a and b show the comparison of wind vectors during 2012, while c and d show wind comparison during 2013.

Table 3. The error statistics of the comparison between CCMP and buoy wind data

Scatterometer dataset	Number of collocations	Wind speed			Wind direction		
		Bias/(m·s ⁻¹)	RMSE/(m·s ⁻¹)	R	Bias/(°)	RMSE/(°)	R
CCMP (2012)	1 210	0.47	1.61	0.80	2.31	29.78	0.89
CCMP (2013)	903	-0.08	1.57	0.82	5.58	35.61	0.86

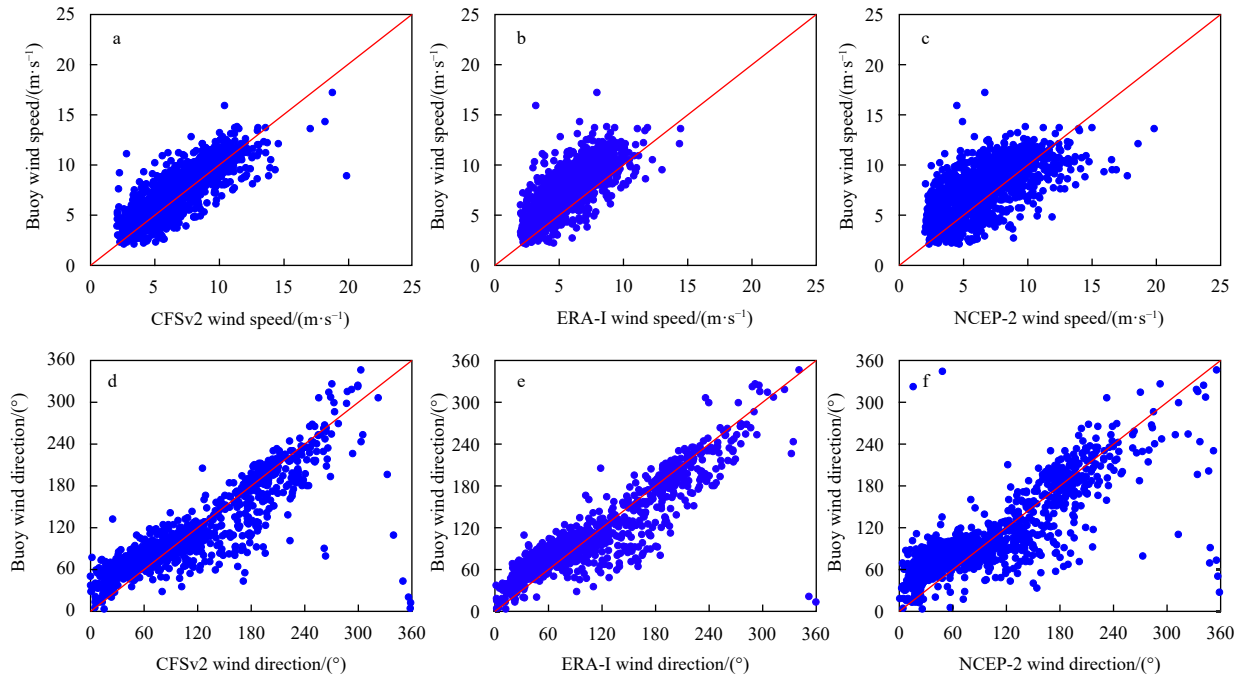


Fig. 5. Scatterplots for the wind speed and direction of the comparisons between the reanalysis and wind data from Buoy 302 during 2012. a. CFSv2 wind speed; b. ERA-I wind speed; c. NCEP-2 wind speed; d. CFSv2 wind direction; e. ERA-I wind direction; and f. NCEP-2 wind direction.

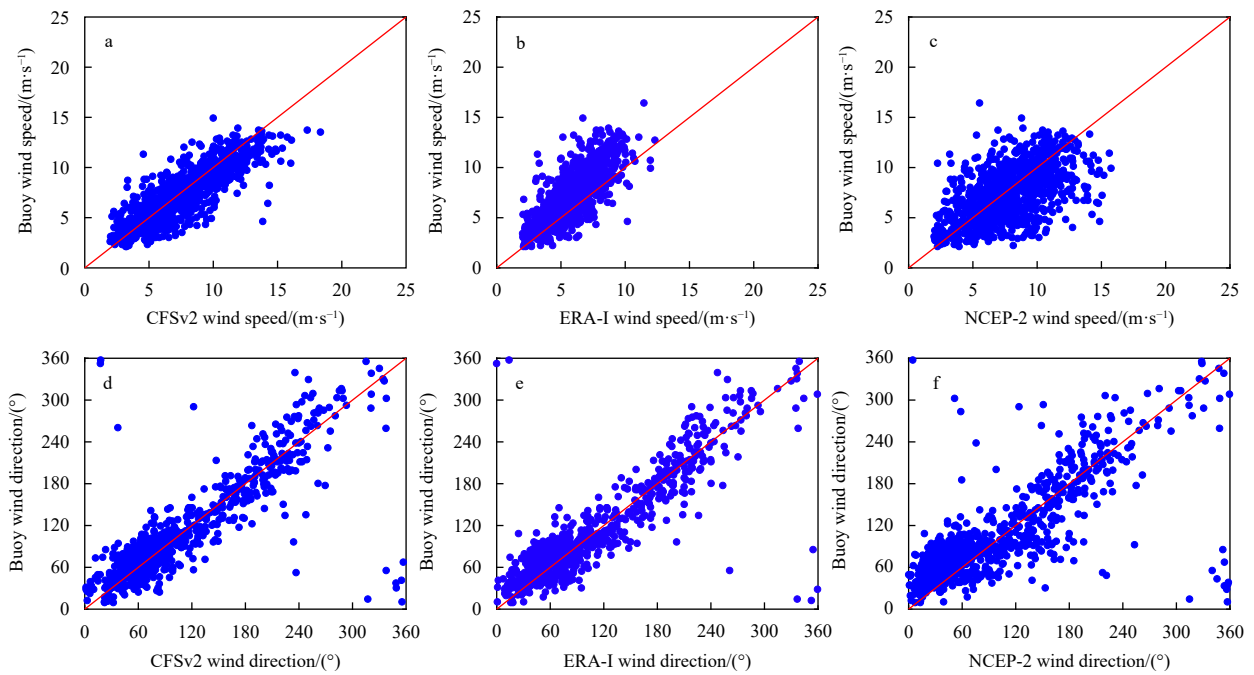


Fig. 6. Scatterplots for the wind speed and direction of the comparisons between the reanalysis and wind data from Buoy 301 during 2013. a. CFSv2 wind speed; b. ERA-I wind speed; c. NCEP-2 wind speed; d. CFSv2 wind direction; e. ERA-I wind direction; and f. NCEP-2 wind direction.

Table 4. The error statistics of the comparison between the reanalysis and buoy wind data in 2012

Reanalysis dataset	Number of collocations	Wind speed			Wind direction		
		Bias/(m·s ⁻¹)	RMSE/(m·s ⁻¹)	<i>R</i>	Bias/(°)	RMSE/(°)	<i>R</i>
CFSv2	1 224	-0.40	1.54	0.82	-1.36	34.48	0.87
ERA-I	1 216	-1.70	1.67	0.76	-2.10	29.46	0.90
NCEP-2	1 200	-0.92	2.29	0.63	-7.26	41.10	0.82

Table 5. The error statistics for the comparison between the reanalysis and buoy wind data in 2013

Reanalysis dataset	Number of collocations	Wind speed			Wind direction		
		Bias/(m·s ⁻¹)	RMSE/(m·s ⁻¹)	<i>R</i>	Bias/(°)	RMSE/(°)	<i>R</i>
CFSv2	925	0.38	1.67	0.83	-2.16	40.42	0.82
ERA-I	911	-1.44	1.69	0.78	-4.88	36.36	0.86
NCEP-2	913	0.40	2.61	0.55	-6.33	51.51	0.74

neous ocean currents in models driven by these wind products. In terms of wind directions, there are pronounced differences in the biases between reanalysis and buoy data, ranging from -6.80° to -1.76° . As suggested in the scatterplots, NCEP-2 wind directions show the largest bias of approximately -7° , which is far beyond the error estimation of buoy data. The RMSEs of wind directions show great deviation from observations, the overall average of which is 38.89° . The correlation coefficients demonstrate that reanalysis winds are consistent with buoy winds, but the values of coefficients vary widely. For example, ERA-I wind direction are more consistent with buoy wind direction than other two reanalysis wind products. However, the correlation coefficients between CFSv2 and buoy winds show accordance in both wind speed and wind direction, the values of which are slightly smaller compared with the evaluation results in open oceans (Peng et al., 2013; Schmidt et al., 2017). The worst correlation is between NCEP-2 and buoy winds, including both wind speeds and wind directions. The average correlation coefficient between NCEP-2 and buoy wind speeds is only 0.59, suggesting its limited ability of representing surface winds.

Table 4 and Table 5 offer a general view of the deviation between different reanalysis and buoy wind vectors, while the distribution of the errors is not entirely clear. To analyse the errors of reanalysis winds at different wind speeds, the biases and RMSEs of wind speeds and directions are calculated in bins of buoy wind speeds of 1 m/s. The results are illustrated in Figs 7 and 8, in which the error bars indicate the biases and RMSEs.

4.2 Analysis of residuals

Figures 7 and 8 show that the wind speed residuals (reanalysis-buoy) decrease with increasing buoy wind speed for ERA-I and NCEP-2 wind products. Besides, the biases when buoy wind speeds over 8 m/s are all lower than 0, which means that these two wind datasets underestimate buoy winds at middle to high wind speeds. Buoy winds are most underestimated by the ERA-I product, suggesting a systematic deviation at almost all the wind speed intervals and a requirement of techniques for the improvement of the accuracy. On the other hand, wind speeds from CFSv2 are the closest to those from the buoys with a maximum bias less than 1 m/s in both years. The deviations at different wind

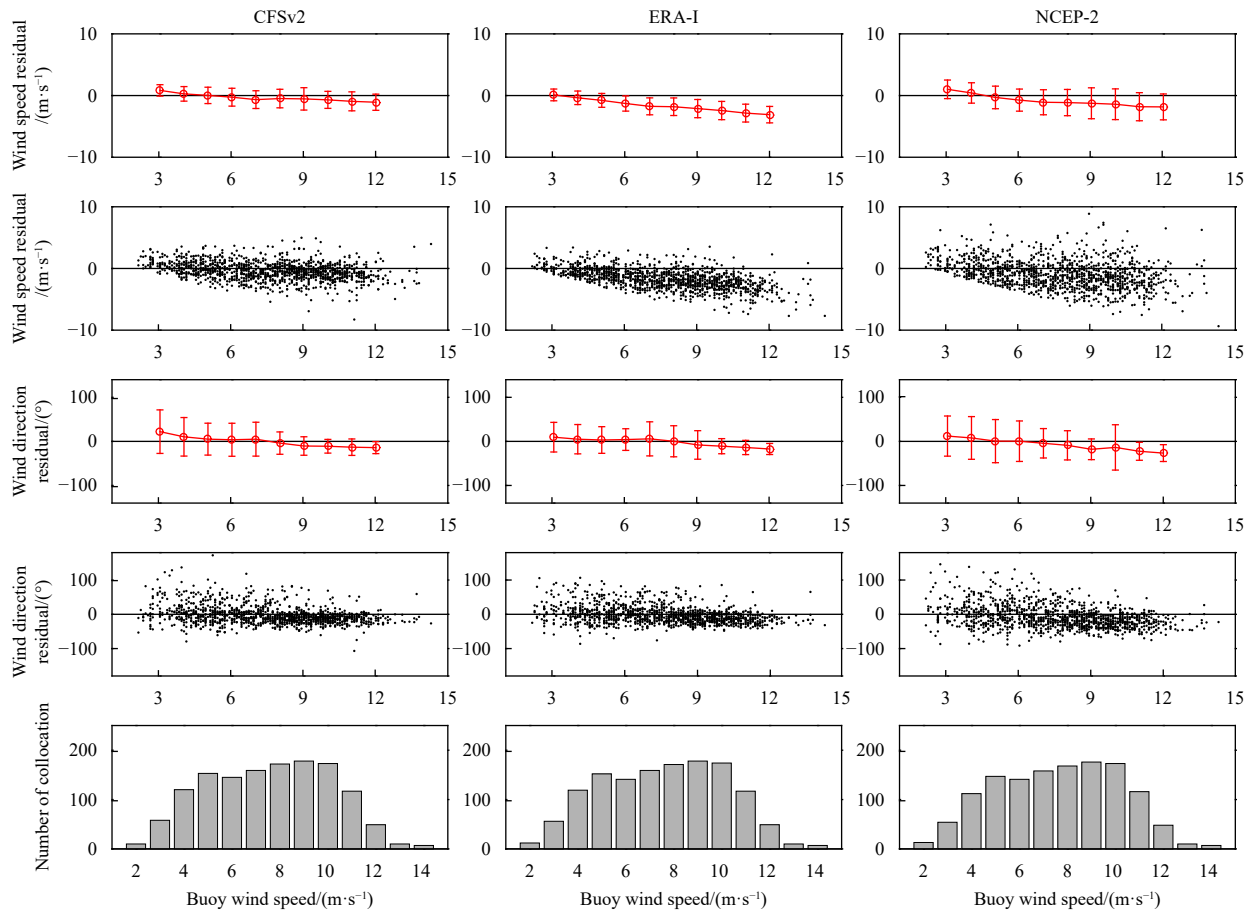


Fig. 7. Dependence of the collocation numbers and wind speed and wind direction residuals (reanalysis-buoy) on the buoy wind speeds during 2012. Buoy wind speeds over 15 m/s (less than 1% of the whole sample) are ignored due to their small statistical value.

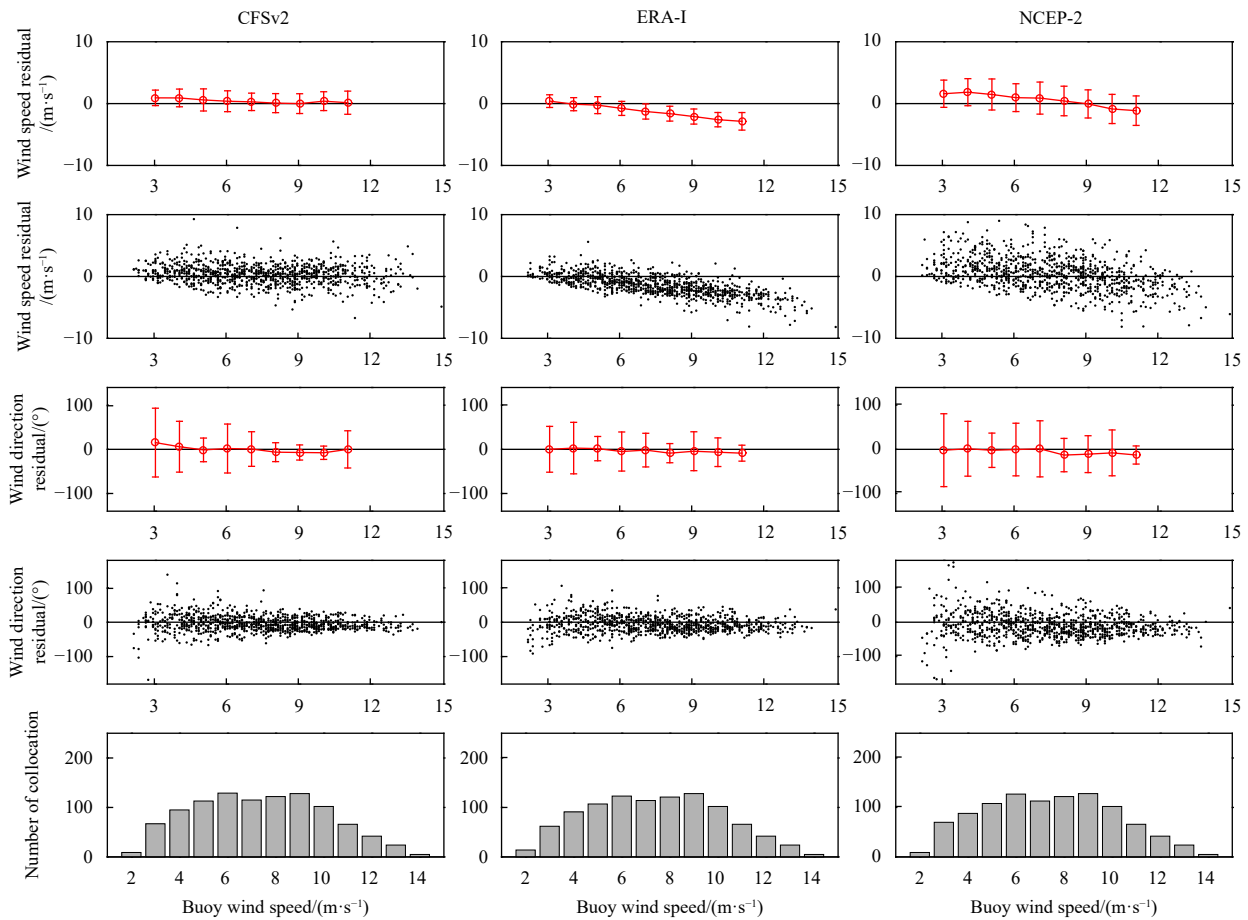


Fig. 8. Dependence of the collocation numbers and wind speed and wind direction residuals (reanalysis-buoy) on the buoy wind speeds during 2013.

speeds are limited at a rather small scale. However, the RMSEs of the reanalysis wind speed show no linear variation with increasing buoy wind speed. This result indicates that there is no dependence on the buoy wind speeds regarding the RMSEs of the wind speed. The RMSEs between the NCEP-2 and buoy wind speeds have the largest amplitude for most of the wind speed intervals.

Compared with the biases in the wind speed, the biases between ERA-I (NCEP-2) and buoy wind directions are insignificant. But there are remarkable RMSEs in wind directions (up to 90°). CFSv2 also demonstrates large RMSEs in wind direction at lower wind speed. The RMSEs of wind direction generally decrease with increasing buoy wind speed, which is the same as the results of Yang and Zhang (2018). This distribution suggests that there is no effective pattern for describing the buoy wind directions at low wind speed.

The errors in the reanalysis wind vectors at different months in 2012 and 2013 are also analysed (Figs 9 and 10, respectively). The comparisons of the RMSEs of the reanalysis wind speeds at different months show consistent accuracy levels during the entire period. But there is a significant difference in the biases of the wind speeds according to the time and reanalysis products. Thereinto, wind speeds from the ERA-I products have negative biases for all 12 months in both years. However, the biases of NCEP-2 wind speeds are not consistent in different years. It maintains negative biases in 2012, while there are positive biases in 2013, especially during the second half of that year. CFSv2

wind speeds, on the other hand, keep close to buoy winds at any time of the year. Therefore, the errors in all three reanalysis wind speed datasets show weak dependence on the time. With respect to the wind direction errors, it is illustrated that significant biases in the wind direction correspond to low wind speeds but with exception of NCEP-2 winds. Significant biases are shown between the NCEP-2 and buoy wind directions during autumn in 2013, when strong northerlies began to prevail. The possible reason is the manifest wind speed errors in the second half of 2013, during which the NCEP-2 winds overestimated the buoy observations. From the above, it is deduced that the accuracy of the wind direction primarily depends on the magnitude of the wind speed as well as the wind speed biases.

5 Discussion

Based on our results, the performance of each wind product varied with respect to time and wind strength. CFSv2 wind vectors are in best consistence with buoy winds in any case. Probability distribution functions (PDFs) of the collocated data also show the different abilities of the three reanalysis products to represent observed wind vectors (Figs 11 and 12). The PDFs of the CFSv2 product and buoy observations imply similar characteristics of the wind speed in these two years, with a slightly negative offset. The distribution of the ERA-I wind speeds has a significantly negative offset from that of the buoy data in both years, indicating that the ERA-I product underestimates the buoy winds. This result has been suggested in the above analysis,

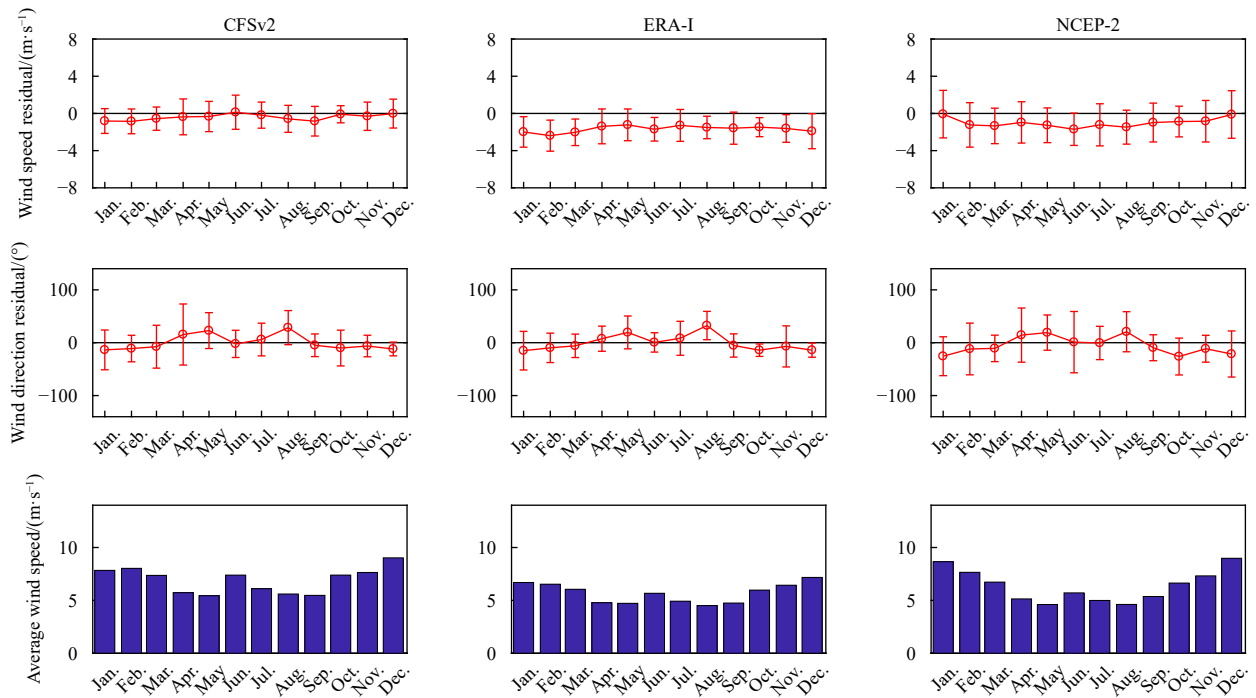


Fig. 9. Errors of the three reanalysis wind vectors (reanalysis-buoy) and the average wind speeds in different months of 2012.

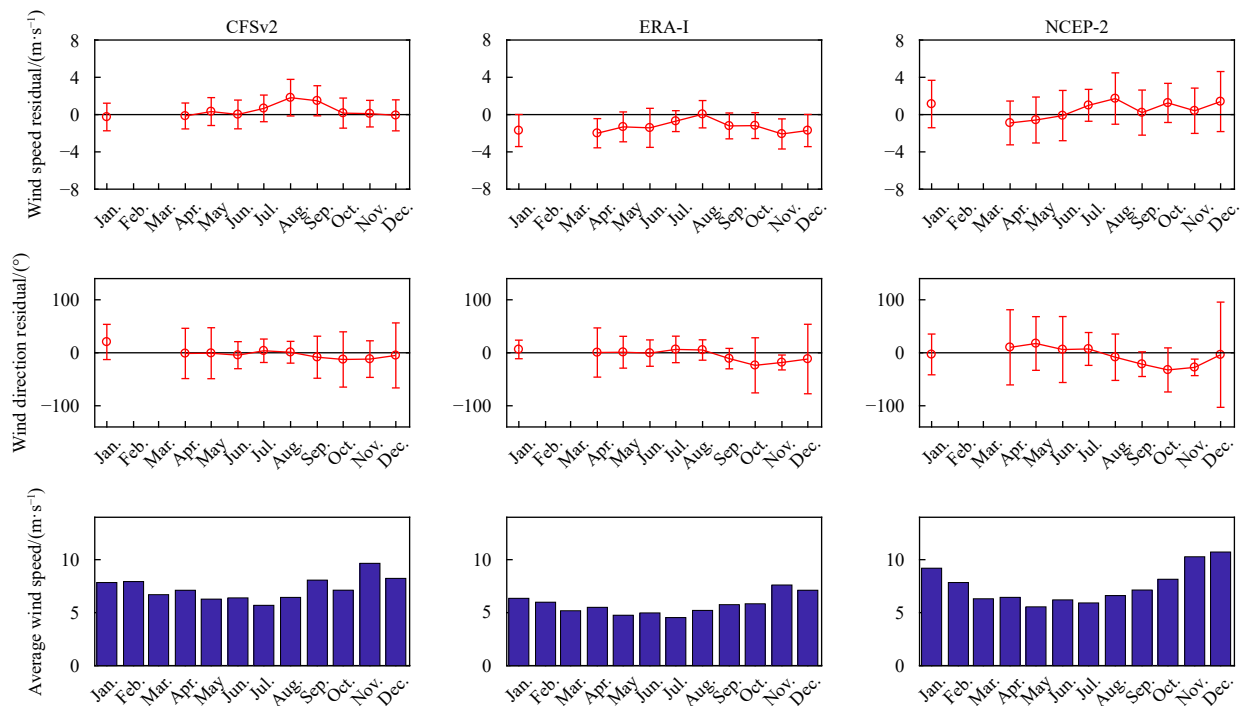


Fig. 10. Errors of the three reanalysis wind vectors (reanalysis-buoy) and the average wind speeds in different months of 2013. Months without bars denote no buoy wind data during these periods.

which has no dependence on time but is heavily dependent on the wind speed. Moreover, both the CFSv2 and ERA-I products provide wind directions that are consistent with the buoy measurements. However, the NCEP-2 wind directions are left-shifting from the buoy winds. The stronger northerlies from the NCEP-2 product are also described in the monthly averaged wind speeds (Fig. 10) compared with the CFSv2 and ERA-I wind speeds dur-

ing wintertime in 2013.

The reasons for the different accuracies in the reanalysis wind products first seem to be connected with the spatial resolution. Note that NCEP-2 has coarse grid spacing ($\sim 2^\circ$), which poorly resolves the spatial variability associated with synoptic and small-scale systems (Chelton et al., 2004; Peng, 2004). Carvalho et al. (2013) confirmed that reanalysis products have limited repres-

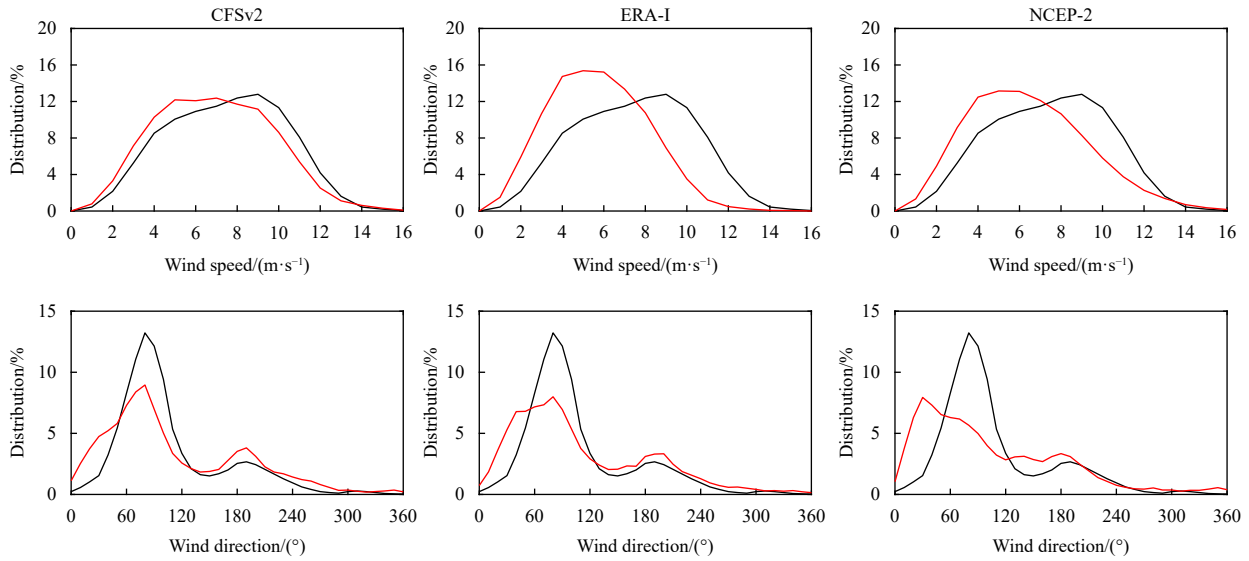


Fig. 11. PDFs of the reanalysis and buoy wind speeds and directions during 2012 in the bins of 1 m/s and 10°, respectively. The black and red lines denote the buoy winds and reanalysis winds, respectively.

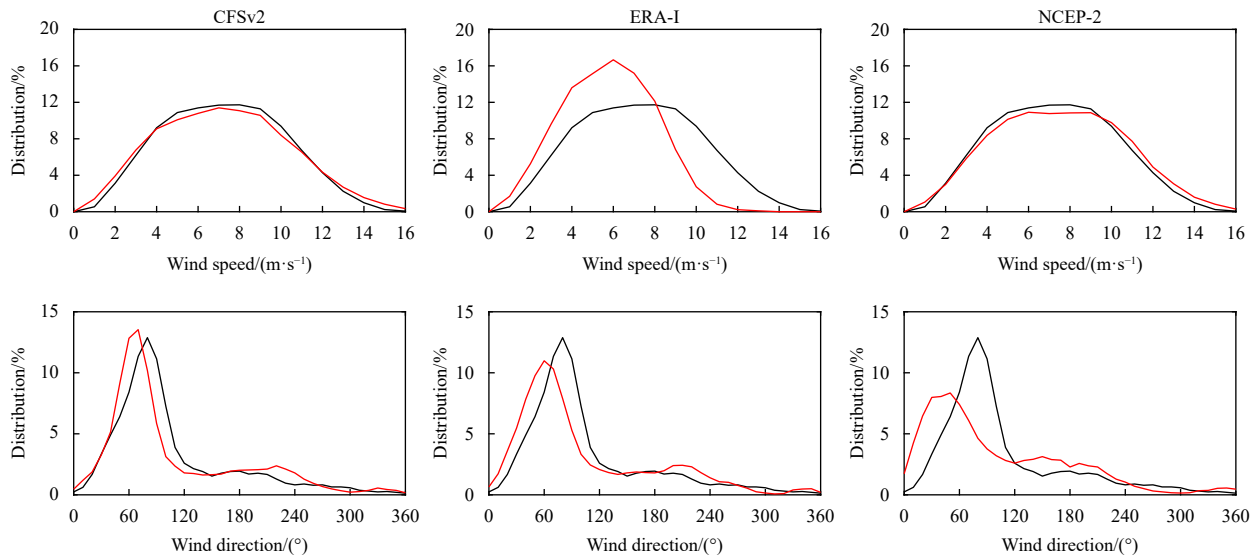


Fig. 12. PDFs of the reanalysis and buoy wind speeds and directions during 2013 in the bins of 1 m/s and 10°, respectively. The black and red lines denote the buoy winds and reanalysis winds, respectively.

entability of synoptic-scale wind perturbations since these products are of lower spatial and temporal resolution, which may lead to the uncertainty between the NCEP-2 and *in situ* buoy measurements. In this study, although we have applied interpolation onto the reanalysis wind products, NCEP-2 winds still have poor performance in depicting buoy winds along the coastal regions. However, the better performance of the CFSv2 wind products may be partly due to the high spatial resolution of the dataset. In fact, if CFSv2 and ERA-I winds are interpolated onto coarse grid as that of NCEP-2, both wind datasets suggest remarkable underestimation of wind speed at almost all the wind speed intervals (not shown). As a result, fine grid blocks adopted in the reanalysis products might have an advantage in describing finer variability in the wind field and meteorological processes.

There appear to be significant systematic errors in the ERA-I

wind speeds, which was also demonstrated by [Chelton and Freilich \(2005\)](#) through a comparison with the wind speeds measured by 22 open-ocean buoys. Such negative biases could be due to inadequacies in the model parameterizations of the atmospheric boundary layer response to the sea surface temperature (SST) or inaccuracies in the specification of the SST boundary conditions ([Chelton, 2005](#)).

In addition, large RMSEs between the reanalysis and buoy wind directions show pronounced inaccuracies in the reanalysis wind products. [Peng et al. \(2013\)](#) noted that variations in meridional winds in tropical oceans are not well captured by wind products. This phenomenon may be due to the basic atmospheric circulation in the tropics, which is dominated by zonal winds. Meridional winds are not well identified due to their small amplitude. However, the buoys we choose are located in the mon-

soon region, both zonal and meridional winds are of equal importance. It is revealed that there is consistent underestimation of reanalysis surface northerlies (Fig. 13), especially in ERA-I and NCEP-2 wind products. Meanwhile, their ability to capture the

variability in weak easterlies (-5 m/s to 0 m/s) is also inadequate. Therefore, the ability to represent low wind speeds is vital for the quality of reanalysis wind products, the lack of which may lead to large uncertainties in the wind direction.

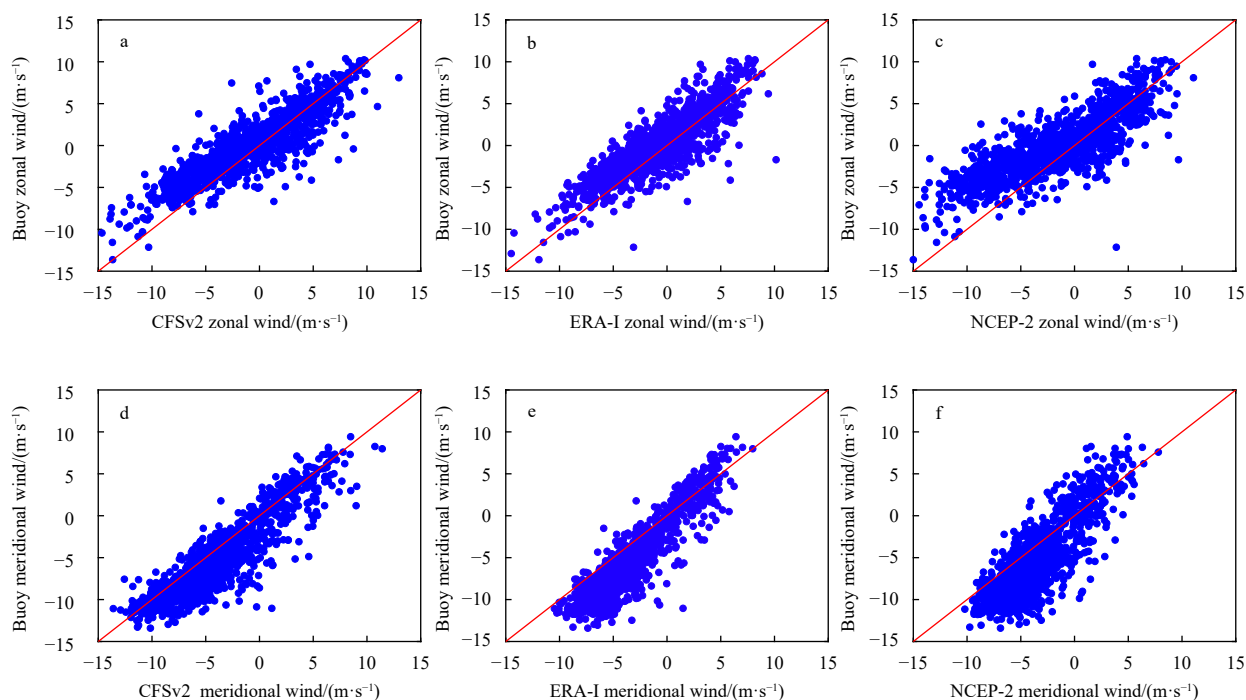


Fig. 13. Scatterplots for the zonal and meridional wind in the comparisons between the reanalysis and wind data from Buoy 302 in 2012. a. CFSv2 zonal wind; b. ERA-I zonal wind; c. NCEP-2 zonal wind; d. CFSv2 meridional wind; e. ERA-I meridional wind; and f. NCEP-2 meridional wind.

6 Conclusions

This study evaluates three historical archived reanalysis wind vectors (CFSv2, ERA-I and NCEP-2) from 2012 and 2013 by comparing them with high-quality buoy data in the coastal regions of the SCS. The original buoy data are processed with extensive quality control techniques, consisting of both data and buoy examinations. The data quality control procedures include checking for range errors, extreme anomalies, and consecutive anomalies, all of which help decrease the number of degraded measurements and improve the validation of sustained marine observations. The buoy data conforming to the requirements above are compared with CCMP surface winds, and the result shows remarkable consistence in both wind speed and wind direction.

Quality-assured buoy winds are collocated with the three reanalysis products each year, in which the wind speeds are mainly in the range of 2–15 m/s. The results show that the average biases (RMSEs) of the wind speed are 0.01 m/s, -1.57 m/s, and -0.26 m/s (1.61 m/s, 1.68 m/s, and 2.45 m/s) corresponding to the CFSv2, ERA-I, and NCEP-2 reanalysis products, respectively, and those of the wind direction are -1.76° , -3.49° , and -6.80° (37.45° , 32.91° , and 46.31°), respectively. The errors in the NCEP-2 product generally have the largest magnitude, indicating the poor accuracy of its wind vectors. The PDFs of the reanalysis wind speeds and directions confirm this conclusion, which also suggests that the ERA-I product significantly underestimates the buoy wind speeds. The analyses of the reanalysis wind vector errors at different buoy wind speeds show that all three reanalysis

is wind speed residuals (reanalysis-buoy) decrease with increasing buoy wind speed. The biases of the reanalysis wind directions are rather small, and there seems to be no clear connection with the wind speed. On the other hand, the RMSEs of the wind direction decrease with increasing buoy wind speed. The comparison of the reanalysis wind vector errors for different months reveals that there is limited dependence on the time regarding the wind direction of the three reanalysis products. It is demonstrated that the accuracy of the wind direction depends on both the magnitude of the wind speed and the wind speed biases.

In general, the CFSv2 wind vectors are strongly consistent with the moored buoy wind measurements. This result indicates that the CFSv2 wind vectors are sufficiently accurate to be used in oceanic numerical forecasting and climate change research.

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